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High concentration photovoltaic systems applying III–V cells

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ABSTRACT

High concentration systems make use of the direct solar beam and therefore are suitable for application in regions with high annual direct irradiation values. III–V PV cells with a nominal efficiency of up to 39% are readily available in today's market, with further efficiency improvements expected in the years ahead. The relatively high cost of III–V cells limits their terrestrial use to applications under high concentration, usually above 400 suns. In this way the relatively high cell cost is compensated through the low amount for cells needed per kW nominal system output.

This paper presents a state of the art of high concentration photovoltaics using III–V cells. This PV field accounts already for more than 20 developed systems, which are commercially available or shortly before market introduction.

Contents

1. Introduction

High concentration photovoltaics (HCPV) still has no measurable contribution to the PV market. Several systems, however, have been developed, and several companies have recently emerged in the market, or will do so in the next couple of years. HCPV system developers promise a cost advantage over flat-plate PV, but most also recognise that this will not be an easy task, especially taking into account how crystalline silicon and thin-film PV are advancing technologically and marketwise. For more details see [1–4]. For instance, in 2009 a relevant price decrease of flat-plate PV due to module oversupply is expected. Therefore, it remains a matter of debate on how the market share of HCPV will play out in the next decade.

In HCPV systems mirrors and lenses are used to concentrate the direct sunlight hundreds of times on high efficiency PV cells. Therefore, they are only suitable for sunny regions. Most available systems apply a concentration factor between 400 and 700 suns, while a few system developers have opted for 1000 suns and above. The record high value of 2000*x* belongs to the California-based company Sunrgi [1]. The main idea behind high concentration is to achieve cost reductions through saving in semiconductor utilized. As a comparison, flat-plate PV targets cost reductions through thinner PV layers and lower cost of the PV material used itself.

The dominating PV cell for applications above 400*x* is the III–V cell. There are a few system developers that are currently still using backside contact silicon cells. In those cases, however, the shift to the more efficient III–V PV cell is being demonstrated or

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considered. For instance, US company Amonix is one of the first companies to develop a HCPV system and has worked traditionally with silicon PV cells. Nevertheless, the company is now demonstrating its system using III–V cells.

Proper optical and thermal management as well as high precision tracking are basic conditions for the correct operation of a HCPV system. The market success of a system will depend on the achievement of high performance, high reliability and low kWh cost. Taking into account that flat-plate PV is already well established, it is believed that a cost advantage of at least roughly 10% will be necessary to convince installers to do the switch. Such an advantage can eventually be achieved. For example, the California-based company SolFocus has created a cost reduction roadmap in which systems would be installed in a few years at \$2.5/W. The scenario counts with 28% efficient modules produced at a factory with an annual production of 200 MW. In this case the cost of electricity would be around \$0.10/kWh for an installation in Phoenix, Arizona [1].

HCPV has relatively very low semiconductor material need. The bulk of dependence is on conventional materials like glass, plastics, steel, aluminium, copper, etc. In III–V cells germanium is both an active layer and a substrate and would theoretically form the bottleneck in material supply. According to the world's leading germanium supplier Umicore, proven reserves can assure an annual market supply of 10 GW over the next 40 years. Furthermore, the inverted metamorphic structure of many new III–V cell designs allows germanium to be etched off and recycled.

Few years ago Spectrolab and Emcore were the only III–V cell suppliers. Both have their own in-house HCPV system development. This situation did not give system developers confidence. Nevertheless, today there are several cell suppliers in addition to others with the proper expertise on how to start industrial production.

In the past it has been debated that material shortage problems are more critical in the case of flat-plate PV than HCPV. However, this is not necessarily the case anymore. Production of solar silicon and the number of suppliers has increased tremendously over the last few years. Also the know-how barrier is not as high as it used to be few years ago. In addition to that, the success of modules produced from upgraded metallurgic silicon (UMG) is a major breakthrough, allowing less time and lower investment in bringing new production capacities [5]. Furthermore, thin-film PV implies additional alternatives of flat-plate modules with relatively low PV material need.

Table 1 lists the most important companies developing and commercializing HCPV systems. Details, including optics, cell properties and efficiency are listed. Table 2 gives the details about accomplished and projected production. Among the 22 systems presented, 15 use the Fresnel lens, one uses a total internal reflection lens (Isofoton), two have opted for the Micro-Dish (Greeenvolts and Solfocus), and three apply a dense array receiver (Solar Systems, Cool Earth Solar and Menova Energy). The dominance of the Fresnel lens is apparent.

2. III–V PV cells

III–V cells achieve by far highest PV efficiencies. As the name indicates, they are produced from elements from the 3rd and 5th group of the Periodic Table like gallium, indium, phosphorus and arsenic. Due to the high light absorption capacity of these elements, few micrometers are sufficient to achieve high light-power conversion efficiencies. Germanium, which belongs to the 4th group of the Periodic Table, is used as an active layer in triple-junction cells. III–V cells are grown by depositing multiple thin films using molecular beam epitaxy or metalorganic vapour phase epitaxy. Combining III–V elements, cells of different band gaps can be developed and ordered in a tandem structure. Each cell converts then an interval of the solar spectrum into electricity. For instance, in a triple-junction cell the top cell converts the violet-blue radiation, the middle one converts the green-yellow radiation and the bottom one the red-infrared radiation. The cells could be in theory mechanically stacked; nevertheless, in practice a monolithic cell is preferred. This implies that the subcells are connected in series. As a result, an ideal layout would be achieved if the band gaps are optimized in a way that each subcell generates the same amount of current so that none would act as a bottleneck. This issue confronts in practice limitations. Growing III–V cells with high crystal quality implies that the different layers must be lattice-matched; otherwise, dislocations and other crystal defects would result at the interface of materials with different lattice constants and this would affect the cell efficiency. Effective solutions to this issue are being developed with already major

Table 1
HCPV systems using III–V cells.

Company		Optics	x	Cell/receiver		η_m (%)	η_s (%)
Arima Eco Energy	Taiwan	Fresnel lens	476	Spectrolab	1 cm^2	22–25	–
Concentrix Solar	Germany	Fresnel lens	385	Azur	d = 2.3 mm	27	23.5
Daido Steel	Japan	Fresnel lens	550	Azur	49 mm^2	23	21
Delta Electronics	Taiwan	Fresnel lens	470	Spectrolab	1 cm^2	26	23
Emcore	USA	Fresnel lens	500	Emcore	1 cm^2	–	27
Energy Innovations	USA	Fresnel lens	1440	Emcore	1 cm^2	28.8	23–25
Enfocus Engineering	USA	Fresnel lens	$>$300	–	1 cm^2	$>$20	–
Green and Gold	Australia	Fresnel lens	1370	Emcore	1 cm^2	34	28
INER	Taiwan	Fresnel lens	476	Spectrolab	1 cm^2	23	20
Opel International	USA	Fresnel lens	500	Spectrolab	1 cm^2	26–28	–
Pyron Solar	USA	Fresnel lens	500	Spectrolab	1 cm^2	22	21
Sharp	Japan	Fresnel lens	700	Sharp	49 mm^2	–	–
SolarTec	Germany	Fresnel lens	600	ENE	4 mm^2	20	17
Sol3G	Spain	Fresnel lens	476	Azur	30 mm^2	24	22.7
Sunrgi	USA	Fresnel lens	2000	Spectrolab	1 cm^2	–	–
Isofoton	Spain	Total internal reflection lens	1000	–	1 mm^2	25	23
GreenVolts	USA	Micro-Dish	625	Spectrolab	1 cm^2	28.5	–
Solfocus	USA	Micro-Dish	500	Spectrolab	1 cm^2	25	23
Solar Systems	Australia	Dish & dense array receiver	500	Spectrolab	1536 $\times$ 1 cm^2	35	30
Cool Earth Solar	USA	Dish & dense array receiver	400	–	–	30	–
Menova Energy	Canada	Segmented reflector	1450	Emcore	116 $\times$ 1 cm^2	26.4	23.2

η_m: module efficiency; η_s: system efficiency. Some of the presented efficiencies here are given by the system developer but are still unverified.

Table 2
Accomplished and projected production of HCPV systems using III–V cells [1].

Company		x	Cell supplier	Production/production capacity		
				End 2008 (kW)	2009 (MW)	2010 (MW)
Arima Eco Energy	Taiwan	476	Spectrolab	300/600	10–25/10–25	100/>100
Concentrix	Germany	385	Azur	500/25000	10/50	50–100/100
Daido Steel	Japan	550	Azur	13.3/300	0.16/1	–/10
Delta Electronics	Taiwan	470	Spectrolab	500/1000	2/2	8/8
Emcore	USA	500	Emcore	950/–	50/–	50/–
Energy Innovations	USA	1440	Emcore	63/–	0.875/1	10–20/10–20
Enfocus Engineering	USA	>300	–	–/–	5/5–10	15–50/30–50
Green and Gold	Australia	1370	Emcore	3/–	–/–	–/–
INER	Taiwan	476	Spectrolab	100/–	1/–	–/–
Opel International	USA	500	Spectrolab	163/6000	10/18	25/36
Pyron Solar	USA	500	Spectrolab	120/2000	1/10	10/50
Sharp	Japan	700	Sharp	–/–	–/–	–/–
SolarTec	Germany	600	ENE	–/–	–/–	–/–
Sol3G	Spain	476	Azur	1500/2000	5–8/8	–/10
Sunrgi	USA	2000	Spectrolab	–/–	20/20	1000/1000
Isofoton (R-TIR)	Spain	1000	–	500/10000	2.5/20	10/50
GreenVolts	USA	625	Spectrolab	2000/–	–/–	–/–
Solfocus	USA	500	Spectrolab	500/10000	15/50	85/100
Solar Systems	Australia	500	Spectrolab	1500/–	–/–	–/–
Cool Earth Solar	USA	400	–	–/–	11.5/–	50/–
Menova Energy	Canada	1450	Emcore	–/65000	22/390	350/780

The 1500 kW installed by Solar Systems until the end of 2008 apply a receiver with backside contact silicon cells. The company is upgrading its receiver to III–V cells.

successes at the National Renewable Energy Laboratory (NREL) in Golden, Colorado and the Fraunhofer Institute in Freiburg, Germany.

In January 2009 the Fraunhofer Institute announced a record efficiency of 41.1% with a 5.09 mm^2 triple-junction cell under a concentration factor of 454*x* [6]. The cell is made out of $Ga_{0.35}In_{0.65}P$ and $Ga_{0.83}In_{0.17}As$ layers on germanium. The Fraunhofer Institute applies metamorphic crystal growth. The semiconductors in these cells do not have the same lattice constant. Thereby, the researchers at the Fraunhofer Institute have managed to localize the resulting crystal defects in a region of the solar cell that is not electrically active. The active regions of the solar cell remain relatively free of defects. In this way, the metamorphic crystal growth enables the use of much larger range of III–V compound semiconductors for growing multijunction cells, so that completely current matched III–V cells could be grown. This is also a good start for future generation III–V cells with 4, 5 and even 6 junctions.

The NREL has developed the Inverted Metamorphic Multi-junction (IMM) solar cell and has achieved an efficiency of 40.8% under 326 suns with it. This triple-junction cell was the record holder at the end of 2008. Spectrolab accomplished the task with 40.7% close behind, followed by Emcore with 40.0% [1].

Commercial triple-junction III–V cells are in the range of 35% to 39% depending on the manufacturer. These already impressive efficiencies are expected to climb to around 45% in a few years with 4-junction cells. The additional junction implies better division of the solar spectrum and lower current densities so that resistive power losses are reduced. The authors of [7,8] estimate on the long run the record cell efficiency to climb close to 50%. Industrial HCPV modules could then achieve efficiencies around 40% and the system efficiency would be a few percentage points behind. As is common in PV, record cells are commercially not available. However, since III–V cells are relatively small (typically 1 cm^2), the efficiency difference between the record laboratory cell and the industrial one is relatively slight. For the moment the difference is roughly of two percentage points.

First research on III–V cells began in the early 1980s. One of the pioneers is the NREL where research started in 1984. In 1994 the NREL achieved a record efficiency of 29.4%. In 1996 US companies Tecstar and Boeing's subsidiary Spectrolab started commercializing III–V cells for space applications. In a few years the relatively new PV technology replaced silicon PV cells in space applications. Also the Fraunhofer Institute started research on III–V cells in 1984, with expectations for terrestrial use [9]. When used on earth these cells could be economically competitive only if used under high concentration. Fig. 1 illustrates qualitatively the efficiency improvement of III–V cells along the years mentioning related developments.

Today there is an increasing demand for III–V cells for the terrestrial market. In the next years demand could grow by 400% annually. Current suppliers of III–V cells are Spectrolab and Emcore from the USA, Azur Space Solar Power from Germany, Energies Nouvelles et Environnement from Belgium, Sharp, and a newcomer from Taiwan, Win Semiconductor. The three largest suppliers are Spectrolab, Emcore and Azur Space.

Figs. 2 and 3 illustrate the relationship between the efficiency and the concentration factor for two different III–V cells. Fig. 2 shows this relationship for Spectrolab's CDO-100 cell taking into account different operating temperatures [10]. Fig. 3 demonstrates the same relationship for Emcore's CTJ cell for operation under 25 °C. Both cells consist of InGaP/InGaAs/Ge on a germanium substrate. The nominal efficiency is measured under a concentration factor of 240*x* and a cell temperature of 25 °C [10]. Within the wide range from

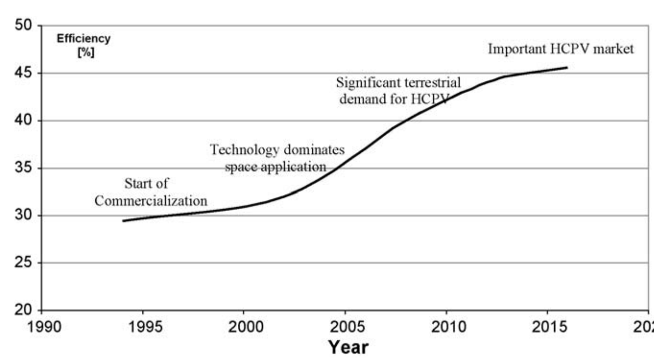

Fig. 1. Efficiency improvement of III–V cells and related development (qualitative representation).

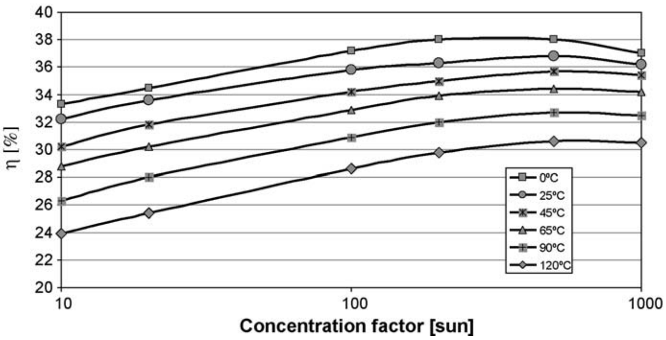

Fig. 2. Relationship between the efficiency and the concentration factor for Spectrolab's CDO-100 cell by different operating temperatures [10].

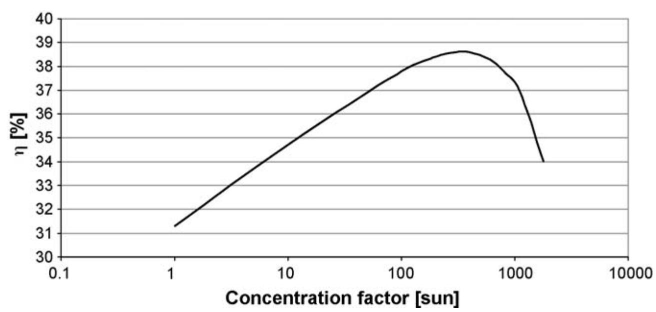

Fig. 3. Relationship between the efficiency and the concentration factor for Emcore's CTJ cell under an operating temperature of 25 °C [11].

100*x* to 1000*x* the maximal efficiency difference is roughly one percentage point. From economical point of view, a concentration factor clearly below 400*x* does not justify the use of III–V cells. For this case the much cheaper backside contact silicon cell is more suitable. On the other hand, concentration factors above 1000*x* do make sense economically despite the efficiency loss illustrated in Fig. 3. Nevertheless, Spectrolab does not recommend the application of its cells under extreme concentration, stating that this would reduce the life expectancy of the cell [10].

In what concerns the influence of the temperature on the efficiency, III–V cells have a relatively low heat coefficient of 0.2%/°C. For every 10 °C rise in cell temperature, the cell efficiency drops by about 0.5 percentage points. Spectrolab recommends maintaining the cell during operation at a temperature below 100 °C. Higher operating temperatures would reduce the cell lifetime. Point focus systems can achieve enough cooling with a heat sink, while dense array receivers need active cooling. Achieving a good solder joint between the cell and the next level substrate is critical to protect the cell from thermal runaway and infant mortality [10].

As previously mentioned, the single cell consists of three subcells in series, each of which absorbs a different segment of the solar spectrum. Should the optics fail to transmit certain wavelengths, one subcell may limit the current output of the entire multijunction cell. The efficiency then would drop and the temperature would increase causing reliability problems.

Due to the fact that the optical and thermal management are issues of the system developer, cell suppliers do not offer universal warranty conditions, but rather system specific. This could result in a shorter life expectancy for the cell than the other system components. A clear difference in this sense does not necessarily constitute a problem in the case of HCPV systems applying a dense array receiver because the receiver could be easily substituted, nevertheless, for point focus systems this would be a serious viability problem. Without any doubt, system developers cooperating closely with their III–V cell supplier have much better chances to win customers' and investors' confidence. On the other hand, HCPV standards are being developed by the International Electrotechnical Commission.

As Table 1 shows, most HCPV system developers have opted for the 1 cm^2 III–V cell. A few system developers apply smaller cells. For instance, German company Concentrix Solar has opted for a circular cell with a diameter of 2.3 mm. German company SolarTec applies also a tiny square 4 mm^2 cell produced by its subsidiary ENE. Spanish company Isofoton applies an even smaller square cell of 1 mm^2. The advantage of smaller cells is the shorter focal distance. Isofoton's high concentration module has a thickness comparable to conventional crystalline silicon modules. A further advantage is the easier thermal management due to the faster heat dissipation of the smaller focus. Nevertheless, tiny cells are less common and their industrial processing is more complex.

Details about cell prices are given on Spectrolab's website where the company reports that its bare 1 cm^2 CDO-100 cell would cost approximately $10 at a production volume of 10 MW per year. With welded interconnects the cell would cost around $14. Prices will decrease with increasing demand and sales volume [10]. Assuming 50 W/cm^2 flux (DNI 1000 W/m^2, 550*x* and 90% optical efficiency) and a nominal cell efficiency of 37.5%, the cell would produce 18.8 W. Under a more realistic operating temperature of 55 °C the cell output would be 18 W. The cell cost is in this case around $0.77/W. Under extreme concentration above 1500*x* the cell would produce more than 40 W and the cell cost would be below $0.35/W. However, reducing the system cost by applying higher concentration is not recommended if it would eventually affect the cell output on the long run or increase the cell infant mortality rate.

3. Systems using the Fresnel lens

As previously mentioned, the most applied HCPV optics is the Fresnel lens. Altogether 15 systems using this optics are listed in Table 1. On this point the system developed by Spanish company Sol3g will be used as an example. This company has carried out several installations, most in Spain and a few in other countries, including Italy, Israel and even Denmark. In September 2008 the company has concluded an 800 kW installation in Flix, Tarragona [12].

Fig. 4 illustrates the optics of the Fresnel lens and the row of 10 lenses of Sol3g. This layout allows building the carousel tracking

Fig. 4. A row of Fresnel lenses from Sol3g (courtesy of Sol3g).

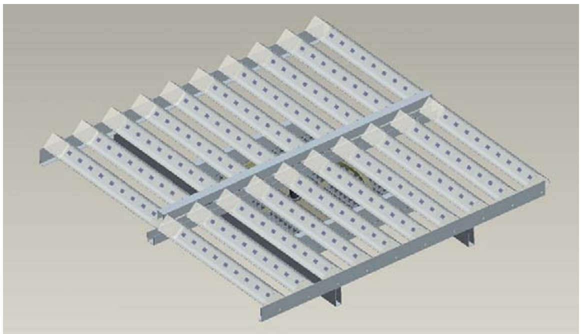

Fig. 5. Sol3g's carousel tracker (courtesy of Sol3g).

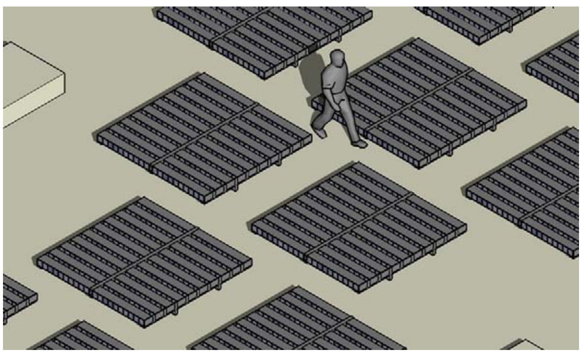

Fig. 6. Sol3g's solar farm (courtesy of Sol3g).

system illustrated in Fig. 5, where the whole platform is adjusted to the azimuth and the rows are adjusted to the altitude. Fig. 6 illustrates how several tracker units are ordered in a solar farm.

This layout illustrated in Figs. 5 and 6 minimizes the wind load. However, Sol3g offers its HCPV system also with conventional azimuth-elevation tracking. This is illustrated in Fig. 7.

As listed in Table 1, Sol3g uses square 30 mm^2 III–V cells supplied by Azur Space Solar. Under the applied concentration factor of 476*x*, the single cell has a nominal output of 3.5 W (DNI 1000 W/m^2) [12]. A homogenizer above each cell transforms the circular focus into a uniform flux over the square cell surface. Sol3g gives warranty details on its website guaranteeing 90% of the nominal power after 10 years, 80% after 20 years and 75% after 25 years [12].

Another HCPV system using the Fresnel lens is the one commercialized by the German company Concentrix Solar. The FLATCON (*F*resnel *L*ens *A*ll-glass *T*andem cell *CON*centrator) technology was initially developed at the Fraunhofer Institute in cooperation with the Ioffe Institute in St. Petersburg. The

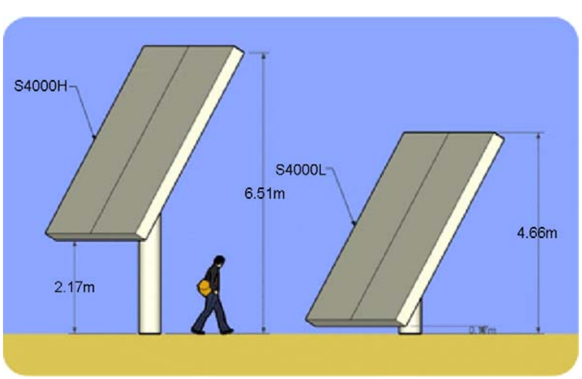

Fig. 7. Sol3g's conventional azimuth-elevation tracker (courtesy of Sol3g).

Fraunhofer Institute started research on HCPV using III–V cells as early as 1984 [9]. Concentrix Solar was founded in 2005 as a spin-off aiming to manufacture concentrator systems based on the FLATCON technology. This technology counts already with 6 years of outdoor experience and climate chamber testing. The developed module uses tiny circular cells of 2.3 mm diameter, which are soldered on a copper plate and subsequently glued on a glass sheet. While the other system developers using the Fresnel lens apply a homogenizer, the Concentrix cell is designed for use without a homogenizer. The front grid has higher density in the center. In an earlier layout the module was hermetically sealed, but then a small valve with a filter was introduced to allow for pressure exchange between the module interior and the exterior. The optical efficiency is reported in [13] to be 82%. The company estimates for large installations (above 1 MW) in sunny locations, a 10–20% cost advantage over electricity production from non-tracking flat-plate PV systems. Energy amortization time for the FLATCON system has been investigated by the Fraunhofer Institute and is 8–12 months for sunny locations. This is even lower than thin-film PV. While the expected lifetime is 25 years, the company gives a 20 years warranty for its modules and power plants in similar condition to crystalline silicon modules [14]. More details about the module manufacturing are available in [15].

Also interesting is the HCPV system developed by the Japanese company Daido Steel. The company is currently the only system developer applying dome-shaped Fresnel lenses. The 550*x* lenses are injection-moulded. The company reports in [16] on long outdoor testing and reliability improvements by overcoming real operation problems such as water condensation and freezing cycles, as well as degradation due to UV radiation. Further details are also available in [17]. For the moment, however, market projections with a production capacity of 10 MW in 2010 are rather low.

System developers take many aspects into account for deciding for a concentration factor: cell efficiency, optical management, thermal management, tracking precision, system economy, III–V cell supply, etc. As Table 1 shows, the highest concentration factor for HCPV systems is currently Sunrgi's 2000*x* module. The company uses 1 cm^2 cells, and therefore needs a square lens with a 44.7 cm side to achieve this concentration factor. This, however, implies also a relatively long focal distance. To this it must be added that the entire module backside is a heat sink. Therefore, Sunrgi's module is notably thick [18]. At 2000*x* the III–V cell operates with an efficiency almost 5 percentage points below its nominal efficiency at 240*x*. As previously mentioned, Spectrolab does not recommend on its website the use of its cells under concentration factors above 1000*x*. Module warranty details are still not available on Sunrgi's website. It is expected that Sunrgi will be finally able through cell saving to achieve a cost advantage above 8% over systems that do not apply extreme concentration. Nevertheless, it is still to be seen if this system cost advantage could eventually be transformed into a kWh cost advantage.

Spanish company Isofoton has not opted for the Fresnel lens but for a total internal reflection (TIR) and a secondary refractive (R) lenses. The last one covers the III–V cell. This TIR-R layout is illustrated in Fig. 8. Due to the tiny 1 mm^2 cell the focal distance is only 20 mm. This allows a compact and a relatively light module. Both lenses are manufactured in acrylic by injection-moulding. According to [19], Isofoton is targeting an installed system cost of €2.5/W already with an annual production of 10 MW.

4. Systems using the Micro-Dish

A few HCPV system developers have opted for the Micro-Dish optics. Two of these will be mentioned on this point, GreenVolts and Solfocus, both based in California. Fig. 9 illustrates the Micro-

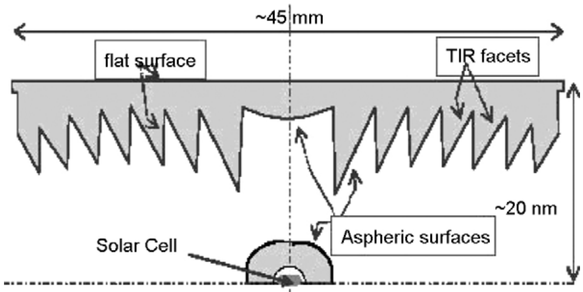

Fig. 8. Isofoton's TIR-R high concentration optics.

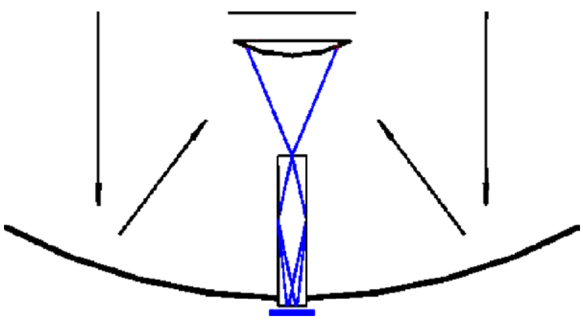

Fig. 9. The Micro-Dish with secondary reflector and homogenizer.

Dish optics. While the Fresnel lens is refractive, the Micro-Dish is a reflective element. The Micro-Dish could concentrate the direct solar radiation directly on the III–V cell, or it could concentrate it on a secondary optics that reflects the radiation back, focusing it in the center of the Micro-Dish where the III–V cell is housed (see Fig. 9).

GreenVolts has developed a system where a glass-made Micro-Dish reflects the direct solar radiation directly on the 1 cm^2 III–V cell. A homogenizer guarantees the uniform flux over the cell surface. A heat sink surrounds the cell and has its shadow outside the Micro-Dish. The unit efficiency is reported in [1] to be 28.5%, which roughly results from 34% cell efficiency (625*x* and ambient temperature +30 °C), and an optical efficiency of 84%. This results in a nominal cell output of 17.8 W (DNI 1000 W/m^2). The system applies a carousel tracker with 164 Micro-Dish units ordered in 10 rows [20]. The DC system output is 2.92 kW.

The system developed by Solfocus applies the Micro-Dish, a secondary reflector and a homogenizer (see Fig. 9) to focus the direct solar radiation 500 times on a 1 cm^2 III–V cell. The secondary reflector has its shadow on the center of the Micro-Dish, where the III–V cell and the homogenizer are located. One module includes 16 Micro-Dish units, while the system consists of 30 modules mounted on a conventional azimuth-elevation tracker [21]. The Solfocus module used originally hexagon-shaped primary mirrors, but the technology has been recently upgraded to square-shaped mirrors so that inactive space is reduced [1]. Still, the optical efficiency of the system is lower than the Micro-Dish unit developed by GreenVolts due to the secondary beam reflection and the shadow the secondary reflector produces. On the other hand, an advantage is that the module backside is used to dissipate the heat. According to [1] the module efficiency is 25% and the system efficiency is 23%. The 2 percentage points difference include the losses through the inverter and the energy consumed by the tracking system.

5. Systems using a dense array receiver

As Table 1 shows, a few system developers have opted until now for a dense array receiver. In a dense array receiver several III–V cells are integrated, which implies a relatively longer focal distance. Due to the larger focus, active cooling is necessary. In theory, useful heat could result here, but taking into account that a low receiver temperature improves efficiency and cell operating conditions, the cogeneration options shrink. The limits of combining power and heat generation in PV systems are detailed in [22]. The advantages of grouping the III–V cells lie rather in the more advanced management that can be assumed for a receiver but not for a single cell. If properly engineered, this can be transformed into an efficiency and reliability advantage.

Australian company Solar Systems has long experience in this field. The company has developed a 500*x* HCPV system based on a 135 m^2 dish and a dense array receiver. The dish consists of 112 curved mirrors of 1.2 m^2 each. The receiver is an array of close-packed PV cells and is suspended above the focus. It is water-cooled and includes a UV radiation filter. It also incorporates current and temperature sensors for real time monitoring and protection. The design allows easy substitution of the receiver. The company has worked on its system since 1990 and counts with a 1 MW installed capacity, although applying a receiver of backside contact silicon cells. The technology is now being upgraded to use III–V cells from Spectrolab. This increases the nominal power to 35 kW, and more can be expected in the near future with the awaited efficiency improvements of III–V cells. Solar Systems plans a new 1.8 MW installation of 48 Dish-units in west Australia in 2010 [23].

Canadian company Menova Energy has also developed a HCPV system for ground-mount and rooftop installation with a dense array receiver and an extreme concentration factor of 1450*x* [24]. This system is illustrated in Fig. 10. A carousel tracker adjusts the azimuth angle, while a segmented parabolic reflector focuses the direct solar beam on the water-cooled receiver. The single receiver includes 116 III–V PV cells of 1 cm^2 each from Emcore and has a nominal DC output of 3.5 kW. The focus is conducted to the cell through a homogenizer. 116 homogenizers form a single element located at the entrance of the receiver. The system efficiency at 23.2% is relatively low if compared to the 30% efficiency achieved by Solar Systems. Nevertheless, the concentration factor is with 1450*x* much higher than the 500*x* PV-Dish.

Another HCPV system developer opting for the dense array receiver is US company Cool Earth Solar. This system has been developed to apply few and cheap materials. A concentrator unit is illustrated in Fig. 11. It consists of a balloon with a dish shaped reflector film in the interior. The dish focuses the direct solar beam 400 times on a water-cooled receiver. To maintain the proper

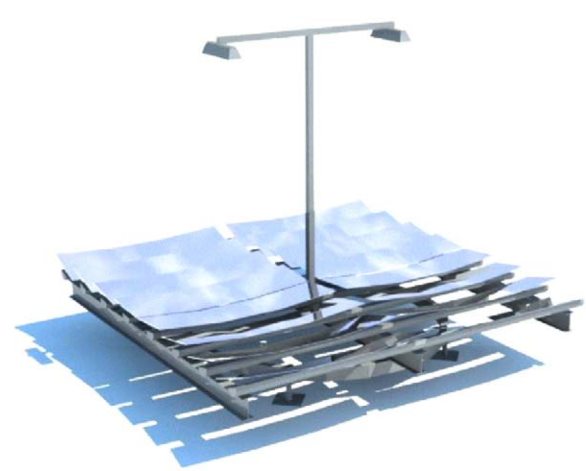

Fig. 10. Menova's High Concentration PV system (courtesy of Menova Energy).

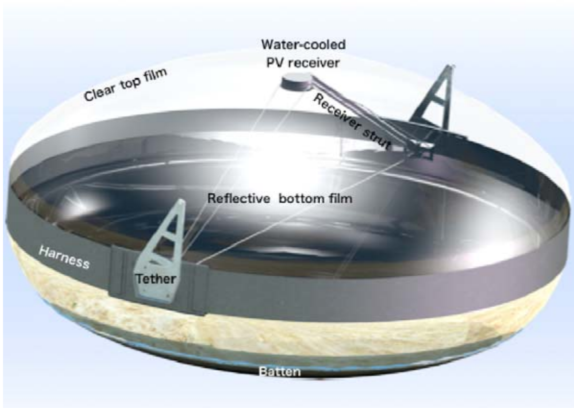

Fig. 11. Cool Earth's dish optics (courtesy of Cool Earth Solar).

optical shape, the pressure within the concentrator is controlled. The system consists of 20 such inflatable concentrator units and applies a tensile truss for the sun tracking [25]. Originally the system used backside contact silicon cells, but it has been recently upgraded to use III–V PV cells.

6. Other systems

Another HCPV system is the 500*x* Cassegrainian Solar Concentrator developed by US company JX Crystals which achieves a module efficiency of 32%. The technology includes very interesting optical management using two focal points. The direct solar radiation is focused by a Micro-Dish onto a dichroic hyperbolic beam splitter, which transmits the infrared light to a GaSb cell and reflects the near visible light focusing it on a dual-junction GaInP/GaAs cell in the center of the Micro-Dish. The square concentrator unit with a 25 cm side has a nominal DC output of 20.2 W, with 15.9 W corresponding to the GaInP/GaAs cell and 4.3 W to the GaSb one [26]. The design permits the use of cheaper cells, while the divided load itself makes thermal management easier. Despite the interesting technology, the company does not seem to be projecting for the moment industrial production, and is rather focusing on a low concentration product [27].

Also different optics has been developed by the California-based company Soliant Energy. The 500*x* concentration factor is achieved with a linear Fresnel lens as a primary optics and a Micro-Trough as a secondary optics. The line focus that the lens generates is reflected back through the Micro-Trough to the center of the lens where a 1 cm^2 III–V cell is housed. The company has developed a module that integrates 35 such concentrator units and 2-axis intra-module tracking [28]. The module is suitable for rooftop installations, and counts therefore with the advantage of consumer near installation. This allows the technology to compete directly with the utility grid prices. A disadvantage of the module is the short distance between the concentrator units, which causes shading losses. For this same reason the company has developed a system where the concentrator units are not grouped in one module, but only connected through the tracking mechanism. The company does not report on its website any market projections [28].

Australian company Solar Systems is not only working on its mentioned Dish-PV unit, but also on a heliostat concentrator technology using a PV receiver housing III–V cells from Spectrolab. The concept is similar to the power tower, but with the huge difference that the solar thermal power plant applies a thermal receiver to supply heat to a Rankine cycle (roughly 400 °C) or a gas turbine (roughly 800 °C), while the PV receiver converts the focused solar radiation directly into electricity. Like in its Dish-PV unit, Solar Systems has opted for a 500*x* concentration factor. The active cooling keeps the solar cells operating around 60 °C. Solar Systems will install the first heliostat concentrator PV power plant in north-west Victoria, Australia, and expects to connect it to the grid in 2013 [23]. The 154 MW power station using several towers will produce 270 GWh electricity annually. With the first project completed in 2013, it is clear that the heliostat concentrator PV technology has developed slower compared to other HCPV systems, but this has also to do with the dimensions of a single power station. The concept of a huge central receiver makes supplementary optics (UV filter, beam splitter, etc.) affordable and permits in this way a more advanced optical management, from which the system efficiency and the life cycle of the receiver would benefit. More on this topic is available in [29,30].

7. The near future of HCPV

In 2007 a couple of hundred kilowatts of HCPV systems using III–V PV cells were installed. On the other hand, in 2008 approximately 6.5 MW were installed. Emcore reports 950 kW installed in Spain, while Sol3g installed around 1.5 MW. In the USA, San Francisco-based GreenVolts has completed a 2 MW project for the California-based utility Pacific Gas & Electric. Spain's ISFOC (*Instituto de Sistemas Fotovoltaicos de Concentración*) installed in 2008 1.4 MW of HCPV systems from Isofoton, Solfocus and Concentrix: 500 kW from Isofoton in Puertollano and Talavera la Reina, 500 kW form Solfocus in Puertollano and Almoguera and another 400 kW from Concentrix in Puertollano and Talavera la Reina [31]. Concentrix installed another 100 kW in Sevilla.

Taking into account the projection of the companies, 200 MW of HCPV would be installed in 2009, and as much as 1.8 GW in 2010. Photon International estimations, however, are much more conservative and foresee only 50 MW to be introduced during 2009 and 200 MW during 2010 [1]. These projections are in reality much more realistic taking into account the short field experience of HCPV using III–V cells. Especially the projections of Sunrgi with 1 GW in 2010 are too high. First, and despite the extreme concentration, Sunrgi will need around 22 million 1 cm^2 III–V cells to achieve the mentioned production of 1 GW, and it is still to be seen if the company could assure such a supply deal. Second, it is still to be seen where this 1 GW would be installed. Finally investors need credible warranty conditions, and it is still to be seen if Sunrgi will offer those for its 2000*x* modules.

Menova Energy is targeting a production of 350 MW in 2010. Next in the list is Arima, which is targeting 100 MW in 2010. The company has opted for a relatively discrete concentration factor of 476*x*, and would need around 10 million III–V cells for the targeted production. Germany's Concentrix is also targeting a production capacity of 100 MW in 2010 with production achieving between half and full capacity. Emcore, with its in-house production of III–V cells would have no problems producing its 50 MW projected for already this year 2009. As a matter of fact Emcore's cell production would be enough to produce 325 MW of its own HCPV system [1].

Taking into account the conservative estimation of Photon International we believe that 50 MW of installed HCPV systems in 2009 and 200 MW in 2010 is not bad news after the 6.5 MW of 2008. Still, HCPV will form a very small segment in the next 2 years within the PV market. How high the installed PV capacity will be in 2010 is still unclear. While the European Photovoltaic Industry Association (EPIA) maintains its conservative prediction of less than 10 GWp [32], Photon International predicts module production as high as 29 GWp, and expects most of these modules to find their way into the market. Due to these uncertainties about the global PV and HCPV market, it is difficult to estimate a market

share for HCPV for 2010. We believe, however, that a discrete 1–2% is a proper judgment.

How the efficiency of HCPV systems will develop in the next years will be explained here with a simple example. Table 1 gives the module and system efficiency of most HCPV systems. As previously mentioned, the nominal III–V PV cell efficiency is its maximal efficiency, which is measured under 240*x*. The cell efficiency in a HCPV system depends on the concentration factor and the operating temperature. On the other hand, the module efficiency includes also the optical losses, which are caused by beam transmissions, reflections and refractions. Shadow or unused space could be taken into account as losses by the system developer or not. Finally, the system efficiency includes the inverter efficiency and the parasitic losses, which are mainly caused by the solar tracking. For example, a system efficiency of 25% would result in a system with the following parameters: Spectrolab III–V cells with a nominal efficiency of 37%, concentration factor of 600*x*, average operating temperature of 55 °C, optical efficiency of 80%, inverter efficiency of 95%, and system parasitic losses of 6%. On the other hand, in 2015 a system could have the following parameters: Spectrolab III–V cell with a nominal efficiency of 45%, concentration factor of 800*x*, average operating temperature of 55 °C, optical efficiency of 85%, inverter efficiency of 97%, and parasitic losses of 4%. This system would have an efficiency of 33%. The lion share of the system efficiency improvement will be achieved by the III–V cell developers. On the longer run cell efficiencies close to 50% and system efficiencies close to 38% can be expected. The success of a system will depend on the ability of system developers to complement the high efficiency with reliability and a low kWh cost.

The energy payback time of HCPV systems is with around 1 year comparable to thin-film PV. As previously mentioned, Concentrix Solar states 8–12 months energy amortization time for its own power plants installed in sunny locations. The lion share of the consumed energy in production goes for the steel of the tracking system, for the glass or plastic of the optics and, depending on the system design, for the heat sinks. For instance, the whole backside of Sunrgi's module is a heat sink and requires much energy in the production, while, on the other hand, the dense array receiver of Solar Systems is water-cooled. The highly efficient thin-film III–V cell itself has an energy recovery time of a few days in HCPV systems [9]. The energy payback time of HCPV systems will also decrease in the next years due to the improved cell efficiency, which does not add significantly to the energy consumption in the production, while accelerating energy recovery.

Note: We would like to remind on this point that HCPV systems as well as III–V PV cells are undergoing continuous improvements. Some details mentioned in this paper may have changed meanwhile.

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